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EVALUATION OF GLACIER MASS BALANCE BY OBSERVING  
VARIATIONS IN TRANSIENT SNOWLINE POSITIONS

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15. Abstract  During this experiment only a very limited number of scenes were obtained, mainly due to weather conditions (mountain areas in Southwestern Norway are often covered by clouds of various kinds). However, the transient snowline on five outlet glaciers from the Jostedalsgreen ice-cap in Southwestern Norway could be determined from ERTS image No. 1336-102060, when bands MSS 5, 6 and 7 were combined in an additive colour viewer.  The snowline was situated at a very low altitude at the time of imagery (24 June 1973) indicating that glacier melt was behind normal schedule, a fact that has a hydrologic bearing: one could expect less melt water in the streams.  The idea to use ERTS imagery in snowline determinations proved realistic and relatively easy to apply in practice. The method will be useful to estimate the glaciers' mass balance for large areas, provided some ground truth observations are made. Images from the end of the melt season are, of course, vital in this work, because it can be shown that a linear relationship exists between a glacier's mass balance and the height of the transient snowline at the end of the melt season.  On an operational basis, satellite images obtained in the fall will provide valuable information on glaciers' mass balance, and thus also hydrologic data for various users, e.g. for water power engineers. To obtain full benefit from this new technique, it is necessary to have some background data of glaciological nature - which is in Norway readily available.		

## PREFACE

The objectives of this project is to determine the position of the transient snowline on glaciers in South Norway. This information can be used to evaluate glacier mass balance at glaciers where no direct observations are made, because there is a certain correlation between the height of the transient snowline and glacier mass balance. Ground truth observations are conducted on a continuous basis during the entire melt season at selected glaciers. Excellent information about the transient snowline and, the mass balance is thus obtained, and the relation between transient snowline heights and mass balance is therefore known for these glaciers. The idea is to extrapolate this information to other glaciers in the area by means of ERTS imagery.

During the reporting period we have concentrated our efforts on a) identification of glacier tongues that are visible on received ERTS images, b) testing methods to enhance the transient snowline, mainly by additive colour technique and photographic means, c) determining the height above sea level of this line by comparisons with good topographical maps.

It is concluded that the method used is relevant to the problem, and there seems to be good possibilities to define transient snowlines also on relatively narrow valley glaciers, a type which is abundant in Norway. However, in 1973, only one of the received images was suitable for height determinations because a) last winter's snow cover was heavier than normal and b) images were either taken too early in the season or were too cloud-covered. The results originating from this image is shown on maps and in a table in the following text.

It is recommended that in the future, the requested study area should be somewhat enlarged so that imagery of all glacierized basins in Norway should be available - so far only a very limited area was originally requested. Experience has shown that the target area originally requested was too small - during the first year only one or two images could be directly used in the project.

## INTRODUCTION

The transient snowline on glaciers is defined as the boundary between last winter's snow and older snow or ice. It moves slowly up glacier during the summer melt season, and this movement is closely tied to the mass balance of the glacier. The transient snowline will reach its highest positions in years of negative mass balance, whereas it will be situated at relatively low elevations at the end of cold summers, thus indicating a positive mass balance.

Water discharge in rivers from glacierized basins is strongly influenced by glacier behaviour. Glacier retreat, i.e. negative mass balance, causes an increase in annual water discharge because part of the glacier's mass is added to the "normal" river discharge. Inversely, during years of positive glacier mass balance, considerable amounts of precipitation will be trapped by the glacier and stored in solid form. Thus, water is withheld from rivers draining glacierized basins, and this can cause serious problems for water power production.

In the planning procedure for future power plants in Norway, it is necessary to undertake extensive glacier mass balance measurements. Such studies are presently made at 8 selected glaciers in Southern Norway, where continuous observations are made during the entire melt season. These observations include the height of the transient snowline, so a good record is kept of its variation; and relations between its height and the glacier's mass balance is known.

If information of the transient snowline could be obtained from a large number of glaciers, this would make possible a good evaluation of the "state of health" of numerous glaciers (instead of only 8) and thus form a base for very important and useful hydrologic calculations.

## OBSERVATION OF THE TRANSIENT SNOWLINE BY CONVENTIONAL METHODS

In the few cases where detailed mass balance observations are carried out (on the above-mentioned 8 glaciers) the transient snowline is continuously observed throughout the entire melt season. Consequently, a good "ground truth" is obtained for these glaciers.

Experiments have been made to determine the height of the transient snow-

line from conventional photographs and, in most cases it proved possible to determine this height because the photographic contrast between last winter's snow and older deposits on the glacier was good enough for such determinations. This method requires however, good contour maps, but such maps are readily available for all glacier areas in Norway (see for example Östrem 1964, p. 322-336). The author has made a similar study in Western Canada, in which several hundred height determinations were made (Östrem 1973c). Due to the costs of conventional air photography it is only possible to portray transient snowline positions at one single occasion or possibly at a very limited number of occasions. Further, this information is of limited value to estimate glacier behaviour related to hydrologic parameters. Only repeated photography or pictures taken late in the melt season are useful for a meaningful evaluation of the glaciers' mass balance. The possibility to watch an almost unlimited number of glaciers was made available through the ERTS Programme.

#### SATELLITE IMAGERY AND TRANSIENT SNOWLINES

The transient snowline is normally easily detectable on conventional air photographs, and it was expected that similar conditions would be found on satellite imagery, provided good resolution could be established.

Most glaciers in Norway are of the "valley"-type, and the width of the ice stream is in the order of 0.5-1 km for many of them. The expected resolution in ERTS pictures was therefore considered sufficient for snowline determinations in most cases.

The difference in reflectivity from snow-covered parts of the glacier (above the transient snowline) and uncovered parts (below the transient snowline) is larger at the beginning of the summer than towards the end of it.

It was, therefore, doubtful whether or not the transient snowline would be visible on ERTS pictures taken towards the end of the summer - when snowline information has its maximum value for hydrologic calculations.

ERTS imagery obtained from Northern Norway on 29th July 1972 (Image No. 1006-09481) shows, however, that the transient snowline is clearly visible - particularly on MSS band 6 and 7 - on the Seilandjöklen Glacier. The summer of 1972 was unusually warm in Northern Scandinavia, and all glaciers showed a strong negative mass balance. This can be easily seen on the said ERTS picture, because the transient snowline had reached a fairly high position already at the end of July. Such a high position indicates a negative mass balance, and consequently, a surplus of meltwater in the streams.

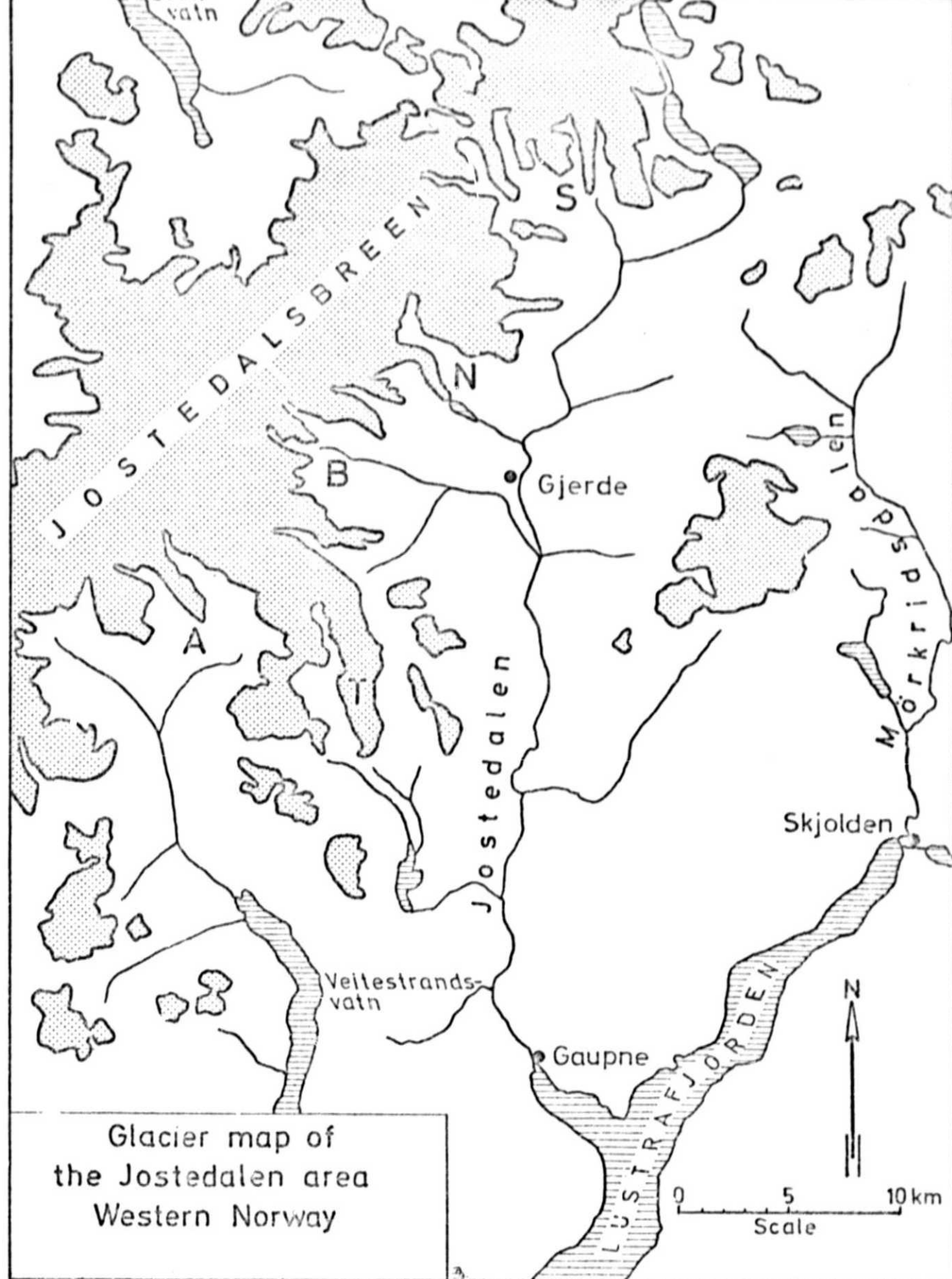
However, this picture was so far the only ERTS imagery that could be used in the study. During the rest of 1972 images were produced for several parts of Norway, but none of them covered glacierized areas so no further studies could be undertaken during 1972. The results obtained from the above-mentioned single image has been reported to NASA in December 1972. The report included colour composite pictures of the Seilandjökulen glacier using MSS band 5, 6 and 7. The transient snowline was clearly visible on almost all combinations produced in an additive colour viewer. The study was also reported in a Swedish and a Norwegian Scientific Journal (Östrem 1973a, 1973b).

### THE 1973 SUMMER SEASON

During the spring of 1973 a number of images showing various parts of Southern Norway were received from NASA. Many of these pictures were either taken early in the season so that all glaciers were completely snow-covered, or they comprised glacier-free areas. No real work related to this project could therefore be done until an image was taken June 24th of Southwestern Norway including many large glaciers (Image No. 1336-10260). On this image all outlet glaciers from the large Jostedalsbreen icecap were clearly visible and on some of these the transient snow line can be detected.

The winter 1972/73 gave unusually large amounts of snow so the transient snowline was situated at far lower elevations than normal at this time of the year. Consequently, exposed ice is visible on a limited number of glaciers only. On the index map, Fig. 1, all glacierized areas are indicated by a grey screen. Further, the outlet glaciers where exposed ice was visible are separately marked by letters.

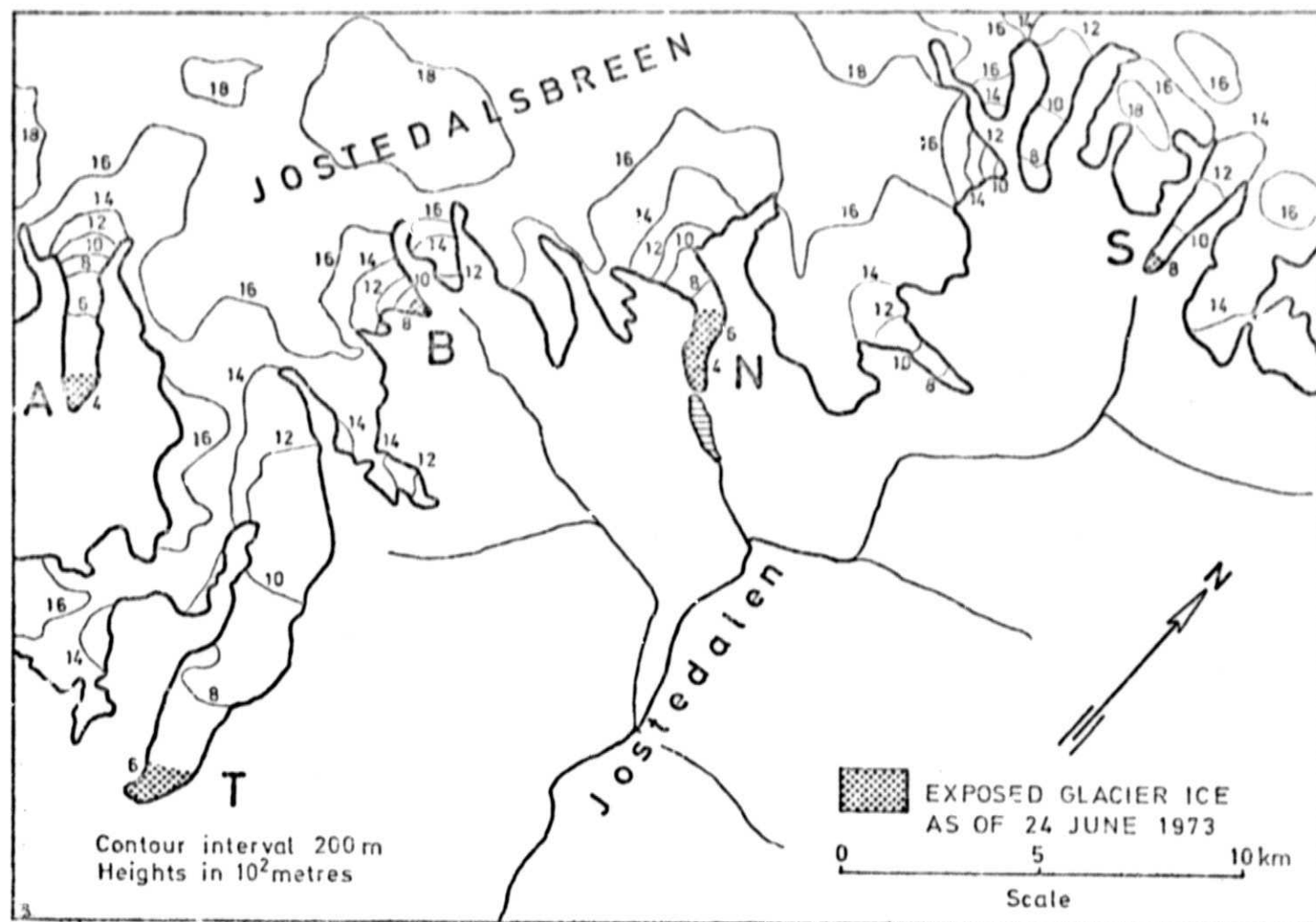
The result from the determinations of the transient snowline are shown on Fig. 2, where the same letters are used for identification. The elevations are shown in Table 1. The resulting figures are consistent enough to prove that the method is realistic and can be used for the purpose, i.e. to determine the height of the transient snowline on Norwegian glaciers. Consequently, it is possible, by repeated imagery throughout the summer melt season, to observe when the transient snowline reaches the critical height of the "equilibrium line", which is a vital concept in glaciology. If the transient snowline stops at this height, the glacier's mass balance equals zero, i.e. the glacier is in a steady state condition.



**Fig. 1** Index map showing all existing glaciers in the area of investigation. Capital letters indicate outlet glaciers where exposed ice was detectable on ERTS Image No. 1336-10260.

A = Austerdalsisen,	outlet glacier
T = Tunsbergdalsbreen,	"
B = Bergsethbreen,	"
N = Nigardsbreen,	"
S = Stegaholtbreen,	"

The identical identification letters are used in Fig. 2



## OUTLET GLACIERS ON THE EASTERN SIDE OF THE JOSTEDALSGBREEN ICE CAP

Fig. 2 Areas of exposed ice determined from a colour composite ERTS Image No. 1338-102060 is here shown by dark screen. The elevations in m a. s. l. of the transient snowline is plotted in Table 1.

TABLE 1

Height of transient snowlines as of 24 June 1973, determined from ERTS  
Image No. 1336-10260.

Outlet glacier	Height in m a. s. l.
Austerdalsbreen	490
Tunsbergdalsbreen	630
Nigardsbreen	660
Bergsetbreen	approx. 800 x)
Stegaholtbreen	" 800 xx)

x) Determination difficult due to an ice fall near the terminus.

xx) Only a very narrow strip of exposed ice seems to be present. Misinterpretation is possible.

If the transient snowline is situated at higher elevations at the end of the summer, the glacier has had a negative mass balance, and a surplus of melt water has drained into the river. Such information is extremely valuable for the water management of glacierized basins.

Until now, no more ERTS images are available for glaciers in South Norway, so further calculations cannot be made from the received data so far.

To determinate the height of the present equilibrium line on a glacier takes long time, and is a very expensive investigation because detailed field measurements must be carried out for several years. Each year's mass balance, expressed in a specific figure, must be plotted versus the final height of the transient snowline for that year. The height of the present equilibrium line can then be determined, compare Fig. 3.

### CONCLUSION

The height of the transient snowline on glaciers is closely tied to the mass balance; it will reach higher altitudes in years of negative mass balance, i.e. when rivers gain extra amounts of melt water from glacier retreat.

The correlation between snowline heights and glacier mass balance is known for 8 glaciers in South Norway (compare Fig. 3) so repeated satellite imagery can be used both to extrapolate similar information to a large number of glaciers (which should be an almost impossible task by conventional methods) and to estimate the mass balance for a great number of glaciers at the end of any melt season. Such information is highly desirable and is of great economic interest.

During the summer of 1973 only one ERTS image could be used for this purpose (No. 1336-10260) and because it was taken very early in the season (June 24) it was unfortunately of limited value. However, it showed a progressing snow melt, and exposed ice was clearly detectable. The transient snowline as of June 24 could be established with good accuracy on 3 outlet glaciers from the Jostedalsgreen ice-cap, and with less good accuracy on 2 other outlet glaciers.

The investigation shows clearly that this method is realistic and can be used for the project.

# NIGARDSBREEN 1962 - 72 South Norway

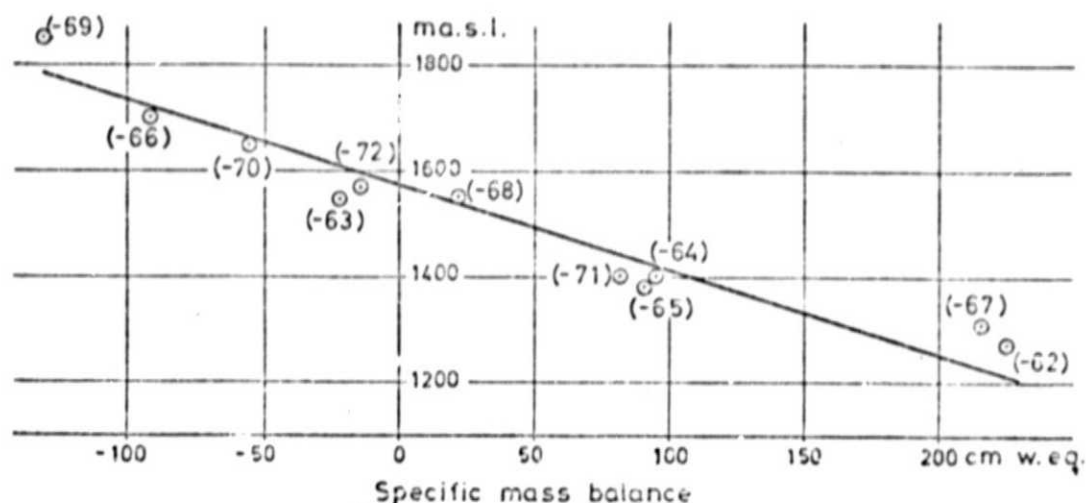


Fig. 3 Mass balance investigations have been carried out on the Nigardsbreen outlet glacier since 1962. The results, expressed as specific net balance (in cm of water equivalent) are here plotted against the height of each year's equilibrium line.

Combining these points, the present equilibrium line height - 1575 m a. s. l. - is obtained for this glacier. If the transient snowline for any season climbs higher than 1575 m, this glacier has a negative year, thus yielding extra amounts of melt water to the stream.

If satellite data are made available at the end of the melt season (late August/early September), a determination can be made quickly of the height of the transient snowline (as shown in this report). In connection with this diagram the actual mass balance of the glacier will be obtained without any more field work or ground truth observations.

This new technique will save considerable amounts of labor and - of course - money. The final results are of vital hydrological interest for water power installations.

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